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Research article

Study of a grid-connected floating photovoltaic power plant of 1.0 MW installed capacity in Saudi Arabia

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A B S T R A C T

To mitigate the environmental effects of burning fossil fuels for power generation, clean, self-renewing, and efficient technologies are being developed and used. Photovoltaics have received attention during the last decades to supplement conventional power production systems. Photovoltaic technology has advanced in the eyes of developers, policymakers, and investors due to the consistently falling costs of photovoltaic panels and improving control systems. Moreover, the efficiency of the photovoltaic is being taken care of by controlling temperature and inventing effective and economical ways of cleaning the panel surfaces. One of the solutions that can minimize the effect of temperature is the floating photovoltaic (FPV). In this study, a techno-economic feasibility study is conducted for constructing 1.0 MW capacity grid-connected FPV power plant in Saudi Arabia. Three locations (Riyadh, Mecca, and Bisha) are chosen where the FPV plants can be installed in water bodies. Meteorological data were obtained from PVSyst software, which is used for simulation purposes. Furthermore, FPV power plants are expected to reduce the evaporation rate from water bodies. The simulation study found the LCOE of 0.053, 0.057, and 0.063 $/KWh for Riyadh, Mecca, and Bisha; respectively. The FPV systems will reduce GHG emissions annually by 390,000 tCO2 at each site.

Nomenclature

AC	Alternating Current
CO_2	Carbon Dioxide
DC	Direct Current
FPV	Floating Photovoltaic
GHG	Greenhouse Gases
Imp	Optimum Operating Current
IRR	Internal Rate of Return
Isc	Short Circuit Current
kW	Kilowatt
LCOE	Levelized Cost of Energy
MPP	Maximum Power Point
MWh	Megawatt hour
NOMT	Nominal Module Operating Temperature
NPV	Net Present Value
POV	Plane Array Irradiance
POV_{NOCT}	Irradiance at Nominal Terrestrial Environmental Conditions
PR	Performance Ratio
PV	Photovoltaic
ROI	Return of Investment

(*continued on next page*)

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(*continued*)

STC	Standard Testing Condition
T	Module Temperature
T_a	Ambient Temperature
T_{NOCT}	Normal Operating Cell Temperature
T_w	Water Temperature
tCO_2	Tons of CO_2
TF	Transposition Factor
Vmp	Optimum Operating Voltage
Vmpp	Maximum Power Point Voltage
Voc	Open Circuit Voltage
WS	Wind Speed

1. Introduction

Photovoltaic systems (PV) are commonly used for direct power generation from the sun for small (isolated and off grid) and large (grid connected) applications due to their sustainability and universality [1–3]. However, many constraints do restrict the deployment of this technology [4,5]. PV systems require massive land areas due to limited efficiency of conversion. According to Rosa-Clot et al. [6], approximately 10,000 m^2 area of land is required for the installation of a 1.0 MW capacity PV system. Other factors that limit the PV technology utilization include the loss of efficiency due to high temperatures and dust accumulation. PV manufacturers characterize the PV cells by a specific maximum power thermal coefficient expressed as (%/°C). This factor can predict the drop in the efficiency for the increased temperature of the PV cell [7]. Therefore, it is necessary to search for new designs and implementation solutions for PV plants to keep the operating temperature low. In recent times floating photovoltaic (FPV) concept has been

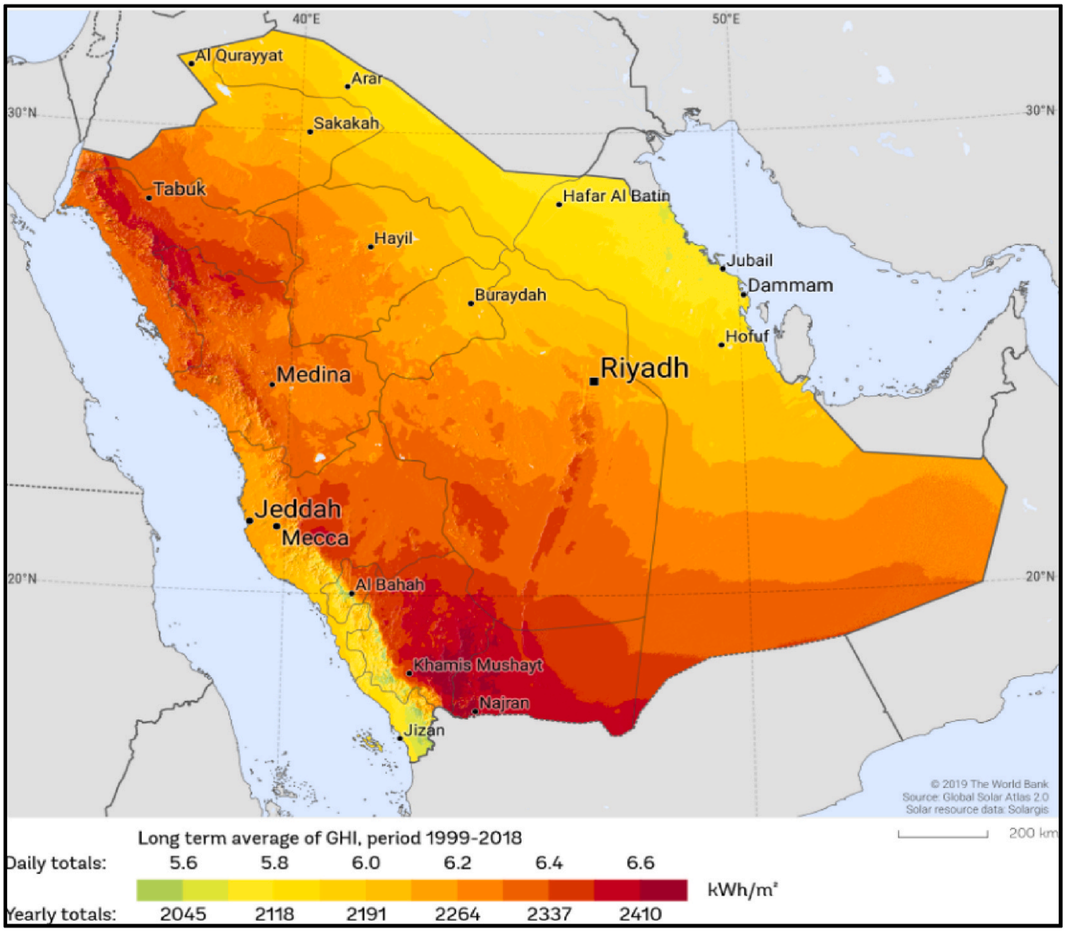

Fig. 1. Solar radiation map for Saudi Arabia highlighting the country's significant potential for solar energy harnessing, with high solar irradiance levels throughout the year

implemented in some countries to limit the rise in the panel's surface temperature. FPV technology is an emerging form of PV application that uses floating structures to allow PV panels to float on the water surface.

The FPV system is mainly comprised of a floating platform, PV panels, anchors, and a distribution system. On the advantageous side, FPV systems tend to reduce water evaporation, which means water conservation is precious for Saudi Arabian in particular and the rest of the globe in general [8]. Water basins can provide natural cooling for the PV modules, which improves the efficiency compared to the systems installed on land [7]. FPV systems appear to be the option for increasing expansion and efficiency. Saudi Arabia has more than 600 dams, small to large water capacities water depths. These dams have the potential to be used to deploy FPV systems to produce power. Saudi Arabia is one of the countries that receives high intensities of solar radiation and has a longer sunshine duration compared to other countries in the world. Figure [1] shows the solar radiation map for Saudi Arabia.

Since the very beginning, Saudi Arabia counted on crude oil to produce electricity. According to Saudi Arabia's Vision 2030, it has planned for a 50 % share of renewable into its energy mix of today through wind, solar PV, solar thermal, geothermal, and waste-to-energy [9,10]. Although Saudi Arabia has high solar radiation intensities, especially in summer, these months have high temperatures in the year. This high ambient temperature tends to decrease the efficiency of the PV system noticeably. Additionally, frequent sandstorms during summer season are another obstacle that adversely affects output efficiency. Hence, effective cooling and cleaning systems are needed to maintain optimum operating conditions of the PV systems to combat the output efficiency problem. Therefore, the FPV systems can tackle some of these issues and can help to improve the performance during the whole year. Usually, the normal dust accumulation is relatively less in water bodies compared to land-based PV systems. Moreover, the water-based cleaning of the panels becomes easy, and the used water goes back to the reservoir.

Floating Photovoltaic is a relatively new technology that is being promoted in areas surrounded by bodies of water such as ponds and dams [11–14]. Many places around the world do not have enough land to install PV panels to generate power, but they are surrounded by water bodies, such as Japan, Singapore, Korea, the Philippines, and others [15]. Table 1 shows some of the existing FPV power plants around the world with different capacities. One of the first FPV plant was installed, for research purposes, in Aichi, Japan [16]. SPG Solar company built a 175 kW FPV plant in California, USA, and by the end of 2014, there were about 22 FPV power stations around the world, with various operating capacities (500 kW–1157 kW) [17].

Cazzaniga et al. [25] conducted a performance analysis of FPV installations and suggested that for maintaining the efficiency such plants tracking, cooling, and concentration to be considered as possible avenues. Their experimental results showed significant enhancement in retaining the system efficiency due to continuous tracking and cooling. Sacramento et al. [26] studied FPV systems at three locations in Brazil and reported an increase of 12.5 % in efficiency compared to ground-based PV systems. Divya et al. [27] conducted a feasibility study of installing 1.0 MW FPV at different locations in Kota, India covering an area of 10,000 m^2. The study reported an annual saving of 37.0 million liters of water from evaporation as a result of water surface covering from the PV panels. Additionally, such an FPV plant resulted in 1714 tons of CO_2 equivalent GHG emissions annually.

Rosa et al. [6] investigated the possibility of using PV plants in different wastewater treatment basins in South Australia. The study stated that 15,000 to 25,000 m^3 of water could be saved from evaporation for each MWp installed capacity [28,29]. Furthermore, the study [6] concluded that if the cost of conventional and floating PV plants is assumed the same, the FPV plant produced more power with an increased efficiency of 10 % compared to the ground-based PV plant. Additionally, a floating structure can save water by shading the water's surface by reducing the evaporation process. This result is also confirmed by research conducted in China to check the development of FPV plants in the country. Craig et al. [30] reported a 40 % savings in water from reservoirs due to evaporation and confirmed similar results in Australia [6]. The researchers reviewed the effect of dust on FPV systems and concluded that these plants have lesser dust accumulation compared to ground-based PV plants [4].

In recent times, the water reservoirs (natural and artificial ponds and dams) have attracted the attention of utilities, developers, and planners toward the deployment of PV panels on the surfaces of such water bodies. Such an option has multiple advantages, such as panel surface temperature control, less dust accumulation, ease of panel cleaning, reduced water evaporation from reservoirs, overcoming the land scarcity in some countries, and retention of output efficiencies of such systems. The annual capacity buildup of FPV plants was 566, 654, 628, and 756 MWDC corresponding to years 2017, 2018, 2019, and 2020, almost a linear increase. The

Table 1
FPV plants worldwide [18].

#	Name of the Company	Location/Country	Plant Capacity
1	Infratech Industries	Jamestown/South Australia	4 MW [4]
2	Bryo	Bubano/Italy	500 KW [19]
3	Kyocera TCL Solar	Hyogo Prefecture/Japan	2.3 MW [4]
4	Kyocera TCL Solar	Yamakura dam/Japan	13.4 MW [4]
5	Kyocera TCL Solar	Hyogo Prefecture/Japan	1.2 MW [4]
6	MANIT	Bhopal/India	1 KW [4]
7	ENERACTIVE	New Jersey/USA	112 KW [4]
8	North Coast Solar	California/USA	252 KW [20]
9	Osesol	Pommeraie - sur - sevre/France	100 KW [4]
10	Ceil et Terre	Berkshire/UK	200 KW [4]
11	CECEP	China	70 MW [21]
12	EGAT	Sirindhorn Dam/Thailand	45 MW [22]
13	Sembcorp Floating Solar	Tengeh/Singapore	60 MW [23]
14	New Jersey Resources	Sayreville, New Jersey/USA	4.4 MW [24]

cumulative global FPV installed capacity reached 2604 MWDC in 2020, Ramasamy and Margolis [31]. The global market share of FPV installed capacities is shown in Fig. 2. It is evident that China, with a 52 % share, is the leading market of FPV while Taiwan and Japan with respective contributions of 12 % and 10 % take second and third place in the global market share of FPV. Competitive PV panel costs, increasing efficiencies, efficient and ease of maintenance, land scarcity, aggressively increasing renewable energy targets, and available subsidies are the main drivers of fast FPV growth in Asia [32].

Whereas geographic diversity is concerned, presently more than 60 countries are actively working on the deployment of FPV systems, Fig. 3, and are in different stages of designing and development [34]. There are 35 countries which have an estimated 350 operational FPV power plants of different installed capacities totaling 2.6 GWDC. The first ever FPV plant of more than 10 MWp installed capacity came into operation in 2018 and now there are plants of more than 150 MWp capacity in operation [35]. The FPV market is projected to foresee a growth rate of ~20 % during the next five years and Asia is expected to be the leading region to dominate the market with two-thirds of the global demand, mainly driven by China, Taiwan, Japan, Vietnam, South Korea, India, and Thailand [34].

According to VISION 2030, the Kingdom of Saudi Arabia is targeting to achieve a significant share of renewable energy into its existing energy mix. The proposed FPV technology will be an excellent option for the generation power efficiently at places having bounded water bodies. In NEOM, AMALA, and RED SEA projects; such systems will be extremely useful to generate power efficiently and at the same time conserve water by minimizing the surface water evaporation losses. As of 2014, there are 302 dams across the country with total capacities of 2.08 Billion cubic meters of water. Some of these dams are located in Riyadh (48), Mecca (27), Madina (14), Asir (43), Jazan (1), Najran (8), Al-Baha (25), Qassim (8), Tabuk (8), Hail (22), and Jouf (6) areas [36]. Such dams and water reservoirs can be utilized to deploy the floating PV systems and can generate power for the local communities and at the same time minimize water evaporation. As an example, Baysh Dam is a gravity dam on Wadi Baysh about 35 km northeast of Baysh in Gizan, as shown in Fig. 4. Its catchment area is 4843 km^2 and its water volume capacity is 675,000 m^3. Locations of other major dams in Saudi Arabia are shown in Fig. 5.

As a result, the installation of a 1.0 MW floating photovoltaic (FPV) system in Saudi Arabia offers an innovative and pioneering method in the field of renewable energy, especially given the country's unique meteorological and geographical characteristics. Saudi Arabia's desert terrain and abundance of solar resources give a unique chance to use FPV technology. Unlike standard land-based PV systems, FPV systems can employ water bodies to manage land use conflicts, reduce water evaporation, and improve solar panel efficiency through the cooling impact of the water [37,38]. The study's focus on three specific locations—King Fahd Dam, Wadi Namar Dam, and Wadi Hali Dam—adds a layer of regional distinctiveness and importance by addressing the Kingdom's diverse climatic and topographical aspects. Furthermore, this study combines modern simulation methods with local climate data to properly evaluate the energy yield and economic sustainability of FPV systems in these areas. By comparing various sites, the analysis not only determines the most feasible location for initial deployment but also provides a framework for analyzing additional potential sites in the region. The utilization of real-time data and localized environmental characteristics assures that the findings are extremely relevant and useful to Saudi Arabia's renewable energy policy. In addition, this study adds to the small but growing body of knowledge on FPV systems in desert regions, where high temperatures and sun irradiance levels bring both opportunities and challenges. The study's emphasis on techno-economic analysis, including the Levelized Cost of Energy (LCOE) and greenhouse gas (GHG) emissions, provides a thorough evaluation that weighs environmental advantages against economic feasibility. This combined emphasis on sustainability and cost-effectiveness is critical for increasing FPV usage in areas with similar climate circumstances. Thus, the study's novelty involves its comprehensive approach to analyzing FPV systems suited to Saudi Arabia's specific conditions, paving the path for more widespread

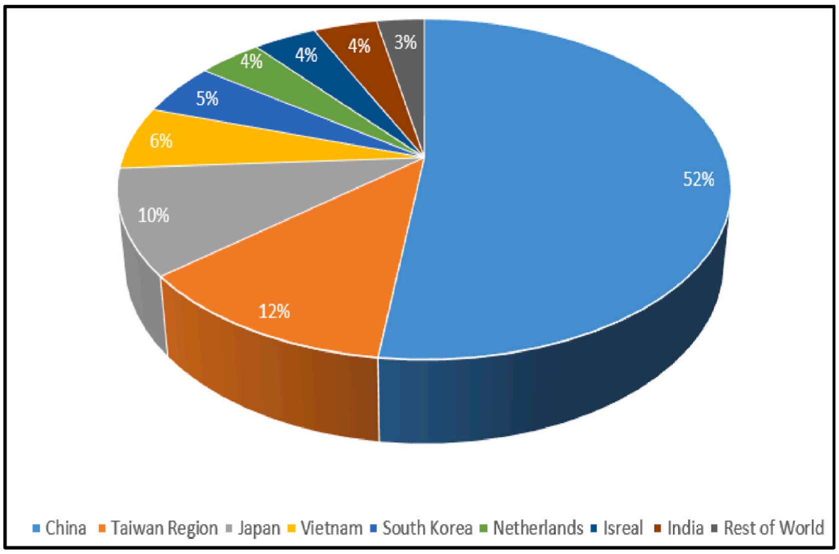

Fig. 2. Global FPV market shares by installed capacity, Cox [33].

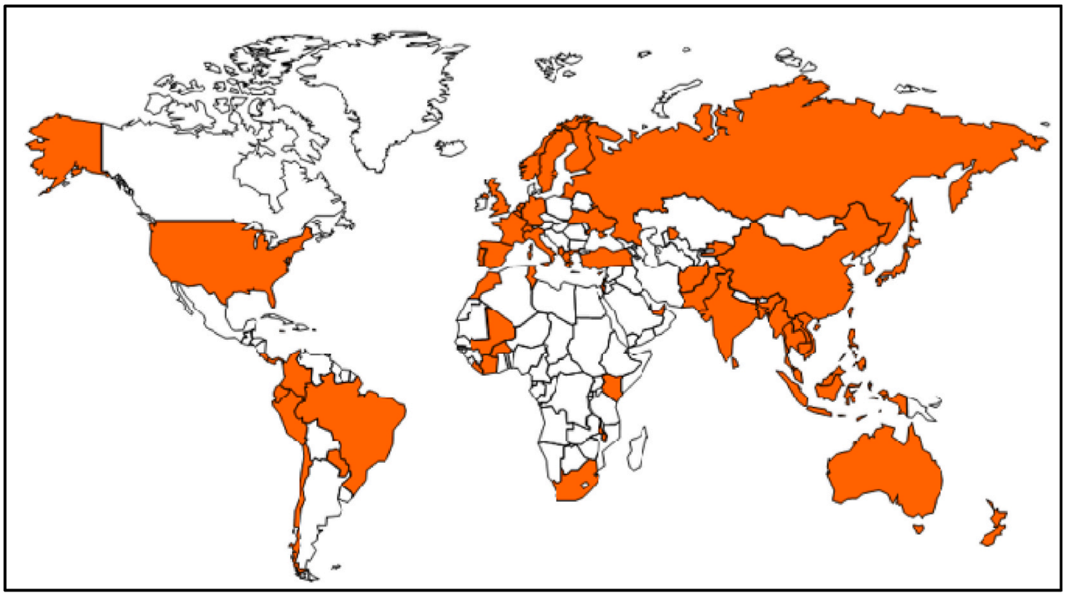

Fig. 3. Countries with current FPV installations [34].

Fig. 4. The Baysh, (King Fahd), dam near Gizan.

implementation of sustainable energy solutions in the region.

2. Material and method

2.1. FPV system description

The scope of the work includes the techno-economic analysis of grid-connected 1.0 MW installed capacity FPV power plants at three locations in Saudi Arabia. The FPV system, under consideration, consists of the following major components.

2.1.1. Pontoon

It is a flotation device with enough buoyancy to be able to float with the expected dead weight of the entire FPV system of 1.0 MW capacity and can withstand the wind load. This platform is designed to accommodate the required number of PV modules in different configurations (series or parallel) [39]. Fig. 6 shows a typical pontoon and a floating structure.

2.1.2. Floats

They consist of multiple hollow plastic floats with effective buoyancy to keep self-floating and join with others to form a pontoon. The floats are typically made of high-density polyethylene, known for its high tensile strength, low maintenance requirement, and corrosion resistance. Floating platforms can also be constructed using glass fiber-reinforced plastic (GRP) [39].

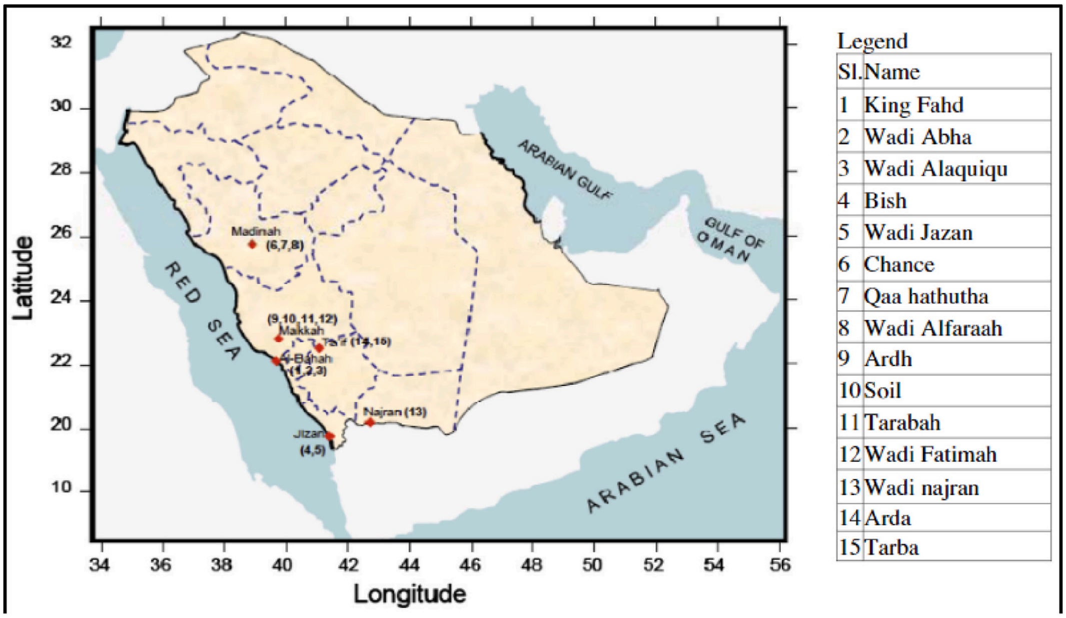

Fig. 5. Locations of major dams in Saudi Arabia [35].

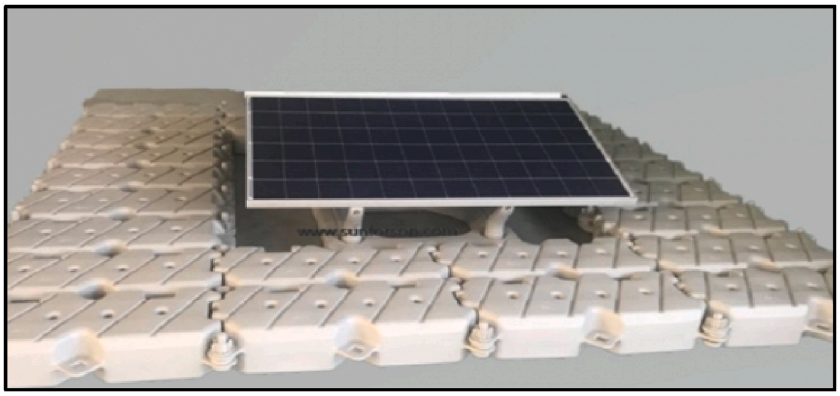

Fig. 6. Floats and pontoon structure [40].

2.1.3. *Mooring system*

Mooring system usually refers to a permanent structure to which a container can be attached. Examples include quays, shipyards, piers, anchor buoys, and mooring buoys. In a floating solar system, the mooring system maintains the panels to remain in the same predefined position and does not allow them to float away [41]. The mooring system for the floating platform can be implemented using nylon wire slings which can be attached to a beach bollard and hammered into each corner. Fig. 7 shows the mooring system that is used in different floating power stations [41].

2.1.4. *PV modules*

Different types of PV modules can be used depending on the efficiency and local environmental conditions 4.5 Cables, connectors, controllers, and inverters: Electricity is drawn from the solar array and evacuated to the grid through proper cabling and control system. Therefore, the power produced must be converted from DC to AC.

2.2. *Site and reservoirs description*

Three water dams in Saudi Arabia are selected to conduct the study by assuming an installed capacity of 1.0 MWp. The three proposed locations are located at different geographical locations. Table 2 presents critical data regarding the three proposed locations for deploying the 1.0 MW floating photovoltaic (FPV) system in Saudi Arabia. These locations are King Fahd Dam in Bisha, Asir; Wadi Namar Dam in Riyadh; and Wadi Hali Dam in Mecca. The coordinates and depth of each site are outlined to provide context for site

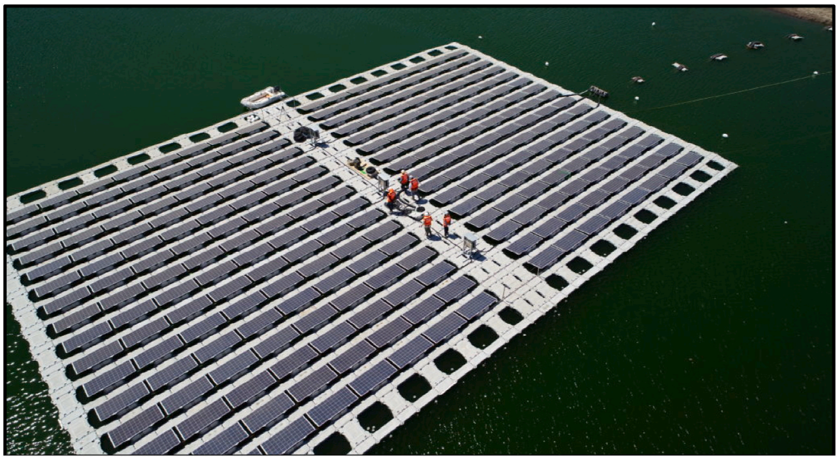

Fig. 7. Mooring system that is used in the FPV power plant [42].

Table 2
Geographical locations and other characteristics of the selected dams.

Name	Latitude (°N)	Longitude (°E)	Depth (m)
King Fahd Dam, Bisha, Asir	19°41	42°29	103
Wadi Namar Dam, Riyadh	24°34	46°40	20
Wadi Hali Dam, Mecca	18°46	41°34	95

selection based on geographic and hydrological characteristics. King Fahd Dam, situated at a latitude of 19°41′N and longitude of 42°29′E, has a significant depth of 103 m, making it a promising site for FPV deployment due to its substantial water volume which can potentially enhance the cooling effect and improve system efficiency. Wadi Namar Dam, located in Riyadh at 24°34′N latitude and 46°40′E longitude, has a shallower depth of 20 m. Despite its lower depth, its proximity to the capital city might offer logistical advantages and easier access to infrastructure and maintenance resources. Lastly, Wadi Hali Dam in Mecca, with coordinates 18°46′N and 41°34′E, has a depth of 95 m, presenting another viable option with a deep water body conducive to FPV installations. The variation in depth among these locations underscores the need to consider both geographic and hydrological factors in FPV site selection. The deeper sites, King Fahd and Wadi Hali are likely to offer better cooling and potentially higher efficiency. Still, logistical and maintenance considerations at Wadi Namar make it a noteworthy alternative. These site-specific characteristics will play a crucial role in the overall performance, feasibility, and sustainability of the FPV system, highlighting the importance of a comprehensive evaluation of both environmental and operational parameters in FPV deployment. The selection of these dams was based on the available surface area that can be utilized for the PV panel installation and the acceptable depth of these dams. Hence, the water temperature can be calculated using the following correlation [43].

$$T_w = 4.29 + 0.55\ T_a \tag{1}$$

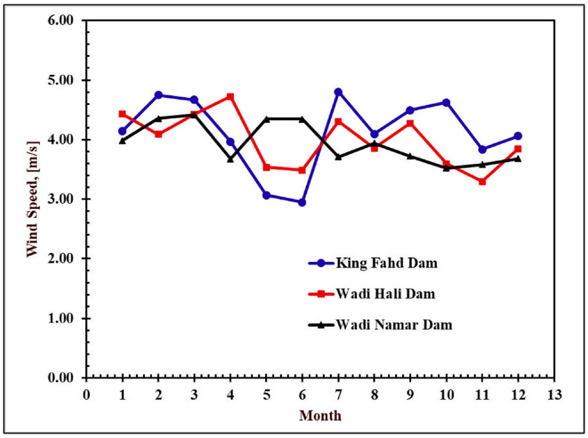

Fig. 8. Monthly average wind speed [m/s] in the three locations King Fahd Dam, Wadi Hali Dam, and Wadi Namar Dam.

Furthermore, Wind speed has a considerable impact on the convective heat transfer process in floating PV systems, determining their technical performance. Higher wind speeds increase the convective heat transfer coefficient, allowing for more efficient heat dissipation from PV panels [44–46]. Fig. 8 shows the monthly average wind speed at the three proposed locations during 2023. These wind speed data were obtained by the NASA website.

Additionally, wind-induced cooling reduces temperature rise on PV panels, improving energy conversion efficiency and extending their lifespan. Furthermore, the presence of cooling water near floating PV systems can improve convective cooling by collecting surplus heat from the panels. This synergistic effect of wind speed and cooling water helps to keep PV panels at lower working temperatures, assuring optimal performance and reliability. As a result, the reduction in temperature non-uniformity throughout the module surface helps to optimize cell performance and reduces the negative effects of hot spots. This is consistent with increasing FPV production by lowering operating temperatures and successfully regulating thermal nonuniformity. The findings highlight the significance of wind speed in minimizing thermal issues and enhancing the operation of FPV systems, particularly in areas with varied environmental conditions [47].

Since temperature is one of the key factors in determining the performance of the PV system, then the module temperature can be calculated by Ref. [48]:

$$T = T_a + \frac{POV}{POV_{NOCT}} \left(T_{NOCT} - T_a\right) \frac{9.5}{5.7 + 3.8\ WS} \tag{2}$$

where, T is the PV temperature, T_a is the ambient temperature, POV is the plane of array irradiance [W/m^2], POV_{NOCT} is the irradiance at nominal terrestrial environmental conditions [800 W/m^2], T_{NOCT} is the Normal Operating Cell Temperature, and WS is the wind speed [m/s].

Table 3 summarizes the global horizontal solar irradiation and average temperature values at three sites. The maximum available solar irradiation is 2.38 MW/m^2/year at King Fahd Dam in Bisha, whereas 2.19 MW/m^2/year at Wadi Namar in Riyadh and 2.07 MW/m^2/year at Wadi Hali in Mecca. Maximum values of solar radiation and ambient temperatures are observed from May to June while the minimum is in December and January months. These values were obtained by using the meteorological data (meteonorm 8.0) in PVSyst.

2.3. PV module selection and sizing of the FPV system

Various types of Photovoltaic panels with different specifications are available in the global and local markets. Hence, certain selection criteria are required to select the best panels to use in the proposed FPV system. The main technical characteristics and the prices of some of the locally available PV panes are summarized in Table 4. Based on these parameters, the PV panel suitability factors are calculated using a simple equation (1), [49].

$$\text{Suitability factor} = \frac{\textit{Maximum Power of the module} * \textit{Efficiency of the module}}{\textit{Price of the module} * \textit{Surface area of the module}} \tag{1}$$

Based on the suitability factor value, the Monocrystalline (LG350N1C–V5) PV modules from LG Company with 350 W peak capacity are chosen. The detailed technical specifications of the selected PV modules are given in Table 5.

To achieve the objective installed capacity of 1.0 MW, thorough planning is required to optimize the layout of photovoltaic (PV) panels while maximizing solar energy absorption. To achieve this goal, 2860 panels, each with a capacity of 350 W, are systematically arranged, requiring an estimated total installation area of 4899 m^2. Tilt angle selection is critical for capturing maximum solar radiation on PV panel surfaces while reducing the angle of incidence. This study carefully selects two distinct seasonal tilt degrees to

Table 3
Meteorological data for the three locations.

Month	King Fahd Dam		Wadi Hali Dam		Wadi Namar Dam	
	Global Horizontal Irradiation, [KWh/m^2/month]	Temperature, [°C]	Global Horizontal Irradiation, [KWh/m^2/month]	Temperature, [°C]	Global Horizontal Irradiation, [KWh/m^2/month]	Temperature, [°C]
January	181.3	15.7	146.8	22.1	142.7	14.9
February	182.4	17.7	145.5	23.2	142.3	18.1
March	211.5	20.3	186.6	25.9	168.4	20.0
April	222.5	22.3	214.4	29.4	205.2	24.9
May	225.3	22.0	206.7	30.9	223.3	31.4
June	218.3	23.0	193.0	30.6	220.1	33.6
July	211.3	24.0	189.7	30.8	228.0	35.2
August	198.6	24.7	178.2	31.0	210.6	34.2
September	195.7	23.1	171.6	31.7	194.6	31.3
October	200.2	20.6	167.4	27.3	177.0	26.6
November	171.2	18.5	140.9	25.6	144.4	18.4
December	163.4	16.1	132.1	22.3	132.5	16.5
Annual Average	**2398.1**	**20.6**	**2072.9**	**27.6**	**2189.1**	**25.4**

Table 4
Selection criteria for PV modules from different manufacturing companies.

#	Module Model	Maximum Power, W	Efficiency %	Area m^2	Price $	Suitability factor
1	SunTech (STP370SB60)	370	20.3	1.820	647.5	6.37
2	SunTech (STP360SB60)	360	19.7	1.820	630.0	6.19
3	SunPower (SPR-MAX2-360)	360	20.4	1.768	299.5	13.85
4	SunPower (SPR-MAX2-350)	350	19.8	1.768	291.2	13.45
5	LG350N1C – V5	350	20.4	1.713	238.0	17.51
6	JA Solar (JAM72S01-350/SC)	350	18.0	1.942	227.5	14.26
7	GreenTech (GTE-360M – 72)	360	20.9	2.020	299.5	12.44

Table 5
Technical specifications of the selected PV module.

Electrical Characteristics of PV Module	
Manufacturer	LG Company
Model	Monocrystalline/N-type
Maximum Power at STC (Pmax)	350 W
Optimum Operating Voltage (Vmp)	35.3 V
Optimum Operating Current (Imp)	9.92 A
Open Circuit Voltage (Voc)	41.3 V
Short Circuit Current (Isc)	10.61 A
Module Efficiency	20.40 %
Operating Module Temperature	(-40 - 90) °C
Maximum System Voltage	1000 V
Power Tolerance	0 ~ +3
Electrical Properties of PV Module (NMOT)	
Maximum Power (Pmax)	262 W
MPP Voltage (Vmp)	33.2 V
MPP Current (Imp)	7.91 A
Open Circuit Voltage (Voc)	38.9 V
Short Circuit Current (Isc)	8.52 A
Temperature Characteristics of the PV Module	
NMOT [°C]	42 ± 3
Pmax [%/°C]	−0.36
Voc [%/°C]	−0.26
Isc [%/°C]	0.03

achieve this goal. Fig. 9 (a, b, c) depicts the precisely calculated optimum tilt angles for both summer and winter at the King Fahd Dam, Wadi Hali Dam, and Wadi Namar Dam sites. During the summer months, the tilt angle is precisely adjusted to near-zero degrees to improve the transposition factor (TF), which is the ratio of incidence irradiation on the plane to horizontal irradiation. The TF reaches its maximum value at zero tilt angle, then steadily decreases as the tilt angle increases, eventually reaching zero at roughly 60°. As a result, for summer conditions at King Fahd Dam, an angle of zero degrees is considered optimum, making (E-W) tracking superfluous because sun radiation is mostly southward. In contrast, during winter conditions, rigorous investigation suggests an optimal tilt angle of 43°, assuring maximum TF. These findings extend to other places as well, with summer and winter tilt angles of (0°, 40°) for Wadi Hali Dam and (0°, 45°) for Wadi Namar Dam. The conscientiously adjusted orientations and tilt angles guarantee excellent energy absorption by the solar modules, which could be aided by potential cooling effects caused by increased convective heat transfer due to wind speed or water evaporation from the dams. Furthermore, to support effective energy conversion, the deployment of two identical AC/DC inverters, each with a capacity of 500 kW and 97 % efficiency, is determined necessary to smoothly convert DC power to AC and feed it into the grid.

3. Result and discussion

The study results for the proposed 1.0 MW installed capacity grid-connected FPV systems are obtained using PVSyst. These results are in terms of economic and environmental parameters like the amount of energy produced per month, and emissions of greenhouse gas (GHG). The results of the analysis, obtained using PVSyst are discussed in the following sub-sections in terms of energy production, economics, greenhouse gas emissions, etc.

3.1. Annual energy production

The solar modules are connected as 22 modules in series with 130 strings. Fig. 10 shows the layout of the system which consists of PV panels, floating system, inverter, and grid-connection system. Fig. 11 shows the normalized energy production per kWp installed

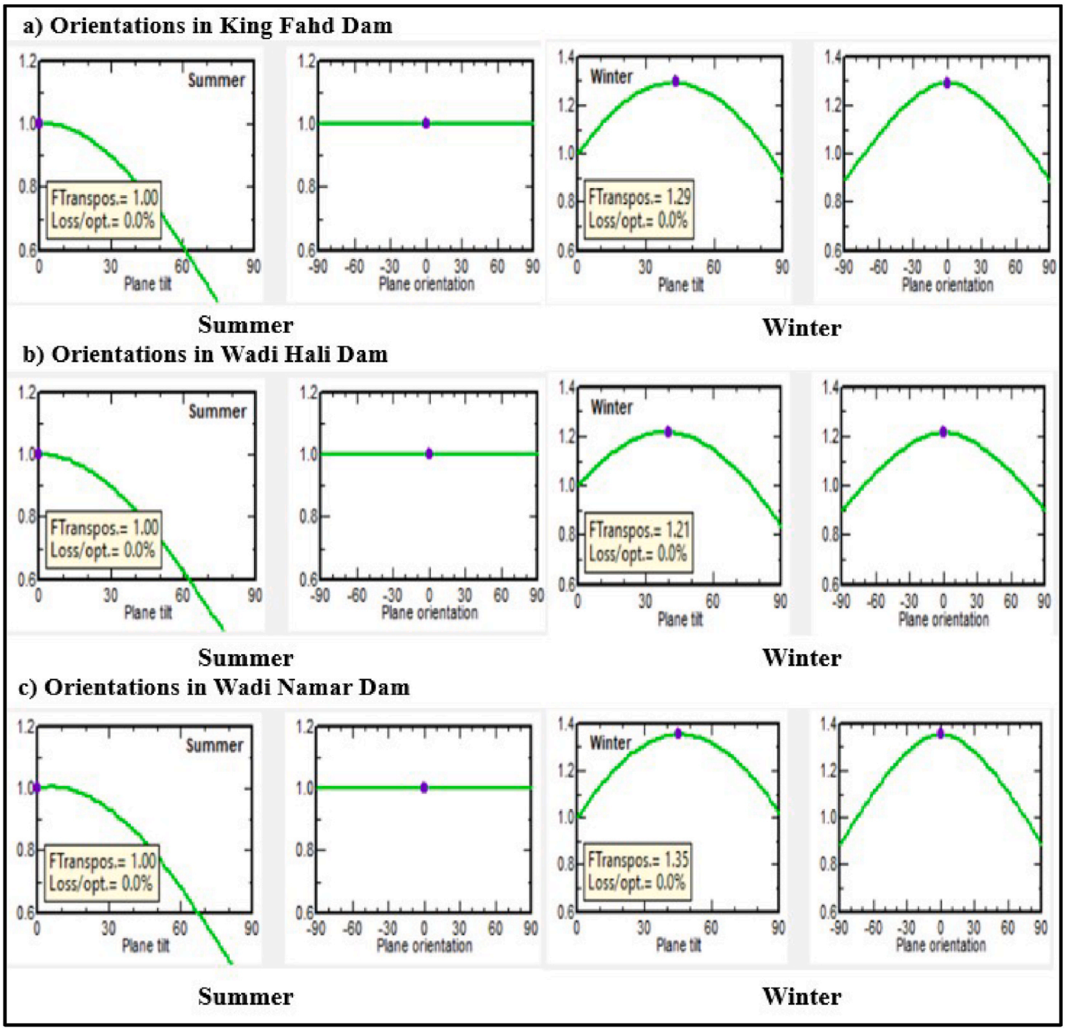

Fig. 9. Orientations at a) King Fahd Dam, b) Wadi Hali Dam, and c) Wadi Namar Dam in summer and winter.

capacity and it describes PV-array losses, system losses (inverter,.), and produced useful energy (inverter output) for King Fahd dam. It can be seen from these figures that the normalized daily energy yield is low during summertime (August to September) compared to the winter period at all the locations and it may be attributed to higher temperatures during these months. The PV output is negatively affected by high temperatures which is a common phenomenon in Saudi Arabia.

For King Fahd dam in Bisha, the solar modules' orientations were considered horizontal (0°) in summer and tilted at 43° in winter (Fig. 12(a)) At this location, the annual energy yield is found to be 2256 MW h with an average performance ratio (PR) of 83.8 %. The performance ratio is defined as the ratio of the effective energy produced by PV to the reference energy that would be produced if the PV system was operating at STC. At Wadi Hali in Mecca, the orientations of the solar system were taken as 0° and 40° in summer and winter; respectively. The proposed FPV system resulted in 1887 MW h of energy yield during the year with a PR of 83.6 %. In Wadi Namar, Riyadh, the orientations of the PV panels at Wadi Namar were 0° in summer and inclined at 45° in winter. The annual energy production was 2083 MW h/year with an average PR of 83.7 %. The three locations show approximately the same average PRs despite the change in average temperature and average incident solar radiation. Fig. 13 shows the minimum, average, and maximum PR values for the proposed locations. The three locations show approximately the same average PRs despite the change in average temperature and average incident solar radiation.

As shown in Fig. 11(a and b), the conversion of the incident radiation into useful energy that is injected into the grid system is higher at radiation values > 6.0 kW h/m2/day. The highest conversion of up to 8.0 kW h/day is observed at King Fahd Dam. In general, the productivity of the system concerning the incident solar energy is high during the entire year. Therefore, the proposed three sites are technically feasible to be used to install FPV power plants.

Fig. 12 shows the energy dynamics and power distribution of the King Fahd Dam. Subfigure 12(a) depicts the energy input/output scatter diagrams, which show the link between the energy supplied and generated by the floating photovoltaic (FPV) system. The scatter plot clearly shows the efficiency and consistency of energy conversion throughout different times of day and year. Subfigure 12

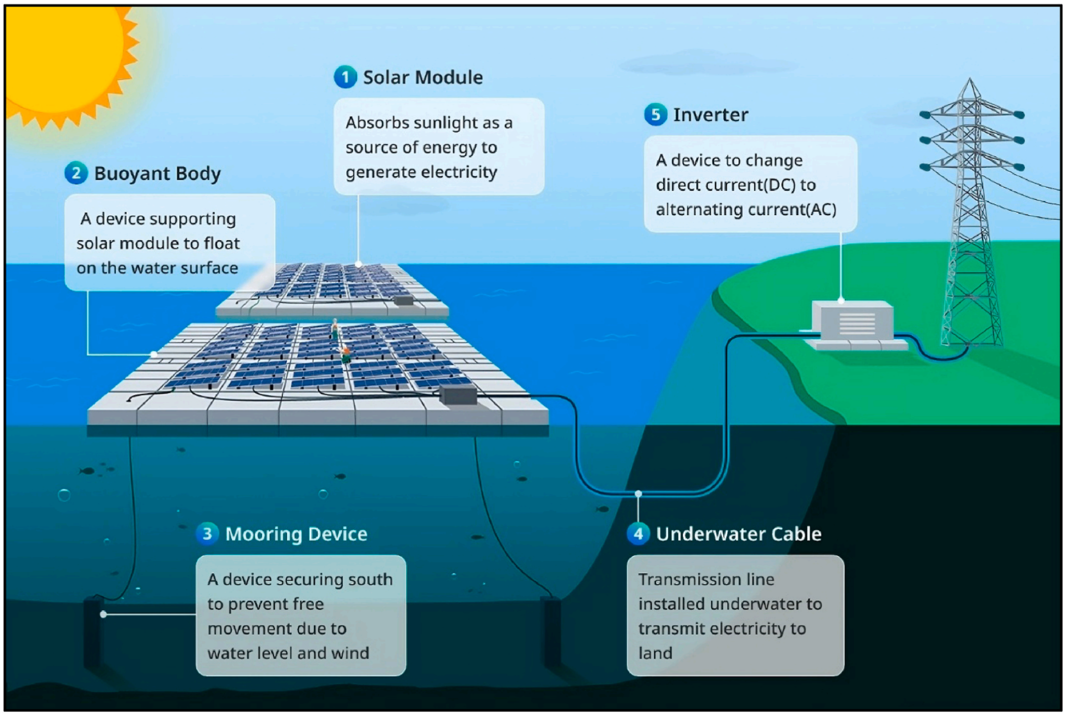

Fig. 10. The layout of the FPV system [43].

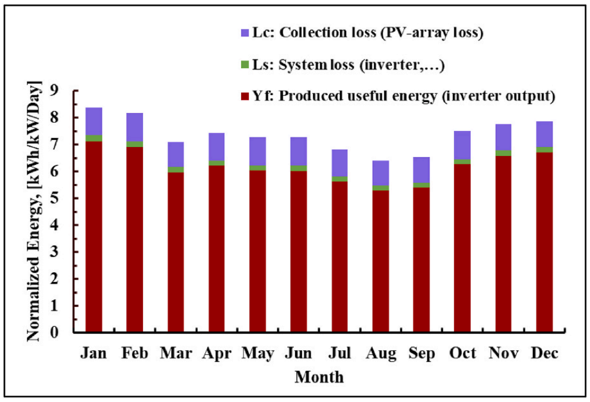

Fig. 11. Monthly normalized energy production variation at King Fahd Dam.

(b) illustrates the power distribution at King Fahd Dam, focusing on how generated electricity is distributed across the dam's various operational segments. This thorough graphic highlights the FPV system's effectiveness in harvesting solar energy, as well as its potential contribution to the dam's overall energy infrastructure.

Fig. 14 shows the energy loss diagram of the system for the King Fahd Dam. The highest losses in the system are due to high temperatures. Thus, it makes the floating application one of the best potential solutions to mitigate such an amount of losses by cooling the panels. At King Fahd Dam, under ideal standard conditions, a total of 2654.0 MW h of energy production could have been possible annually. After different losses (PV irradiance, temperature. module quality, mismatch, Ohmic), a total of 2328 MW h energy could have been produced annually at MPP as can be observed from Fig. 14. With further inverter losses of 3.1 %, as shown in Fig. 8, a total of 2256 MW h of energy could be realized at inverter out and evacuated to the grid during the year.

3.2. Economic analysis

The economic analysis of the FPV system is based on the Levelized cost of energy (LCOE) in $/kWh. The LCOE is the average total cost of installation and operation per unit of the electricity generated over the lifetime of the plant. Earlier, Table 6 summarized the

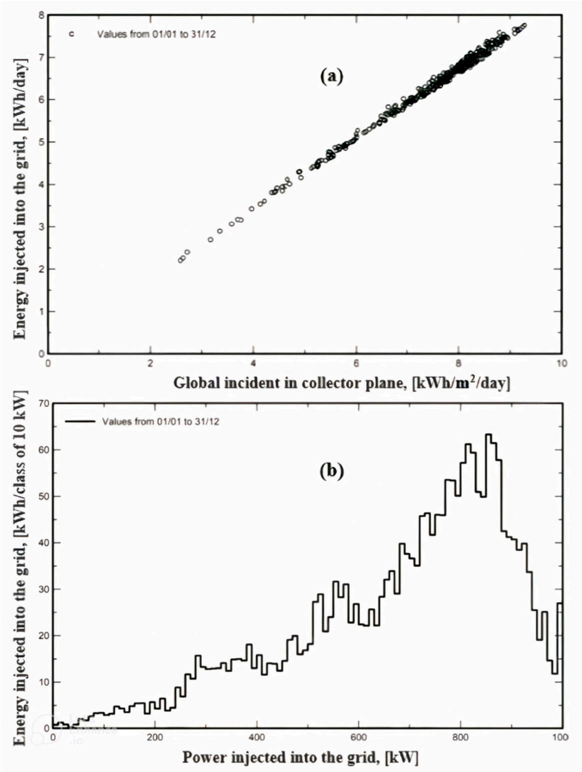

Fig. 12. (a) Energy input/output scatter diagrams at King Fahd dam, (b) Power distribution at (a) King Fahd dam.

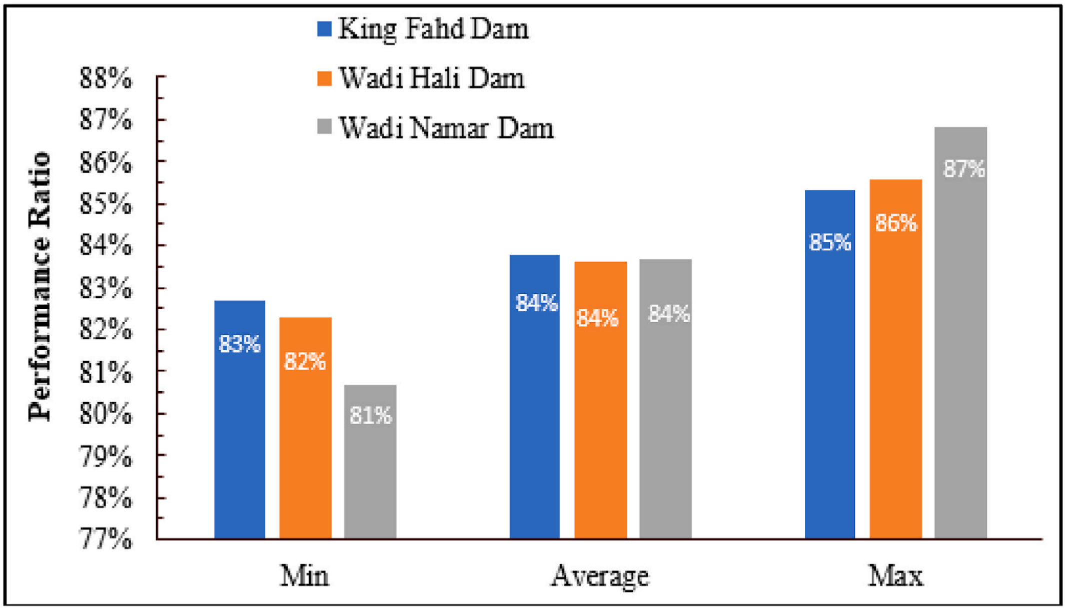

Fig. 13. Performance ratio (PR) at (a) King Fahd Dam, (b) Wadi Hali Dam, and (c) Wadi Namar Dam.

initial cost parameters that are used as the input to the PvSyst software for economic analysis. The capital cost of the system includes the costs of PV modules, a DC/AC inverter, a floating structure with a surface orientation control mechanism, anchoring, construction, and other infrastructure specific to power plants. The operation and maintenance costs were assumed to be 1 % of the total value of the capital cost. The inflation rate is taken as the inflation rate for October 2022 announced by the Saudi National Bank [50]. The discount

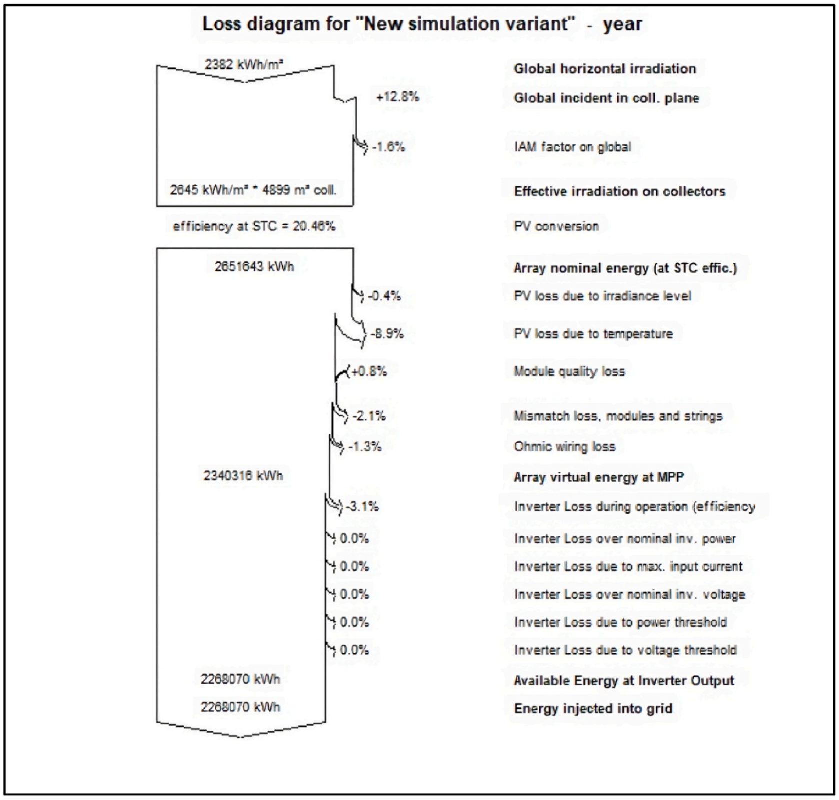

Fig. 14. Losses diagram for King Fahd dam.

Table 6
Economic input data summary.

Name	Value
PV Modules	$ 680,680
Floating System	$ 500,000
Inverters	$ 126,000
Total Capital Cost	$ 1,413,880
Operation and Maintenance	$ 14,138.8
Discount Rate	5 %
Inflation Rate	3 %
Lifetime	25 Years

rate is assumed as 5 % while the plant life is considered as 25 years.

Since the input financial parameters are the same for the three locations, the variation in LCOE refers to the total energy production from each plant. The LCOE is estimated as 0.053 $/KWh, 0.063 $/KWh, and 0.057 $/KWh for King Fahd dam, Wadi Hali dam, and Wadi Namar dam; respectively. Interestingly, the LCOE values are approximately within the range of Saudi Arabia's electricity tariff of 0.048 $/kWh for households and 0.080 $/kWh for industries. Considering the LCOE compatibility with the existing tariff, all the investigated sites have the potential for the deployment FPV power stations with King Fahd Dam being the best site.

To further understand the economics of the proposed FPV systems in Saudi Arabia, simple payback period (SPP), net present value (NPV), internal rate of return (IRR), and return of investment (ROI) are calculated and are provided in Table 7. The simple payback period (SPP) is found to be a minimum of around 12 years the for King Fahd Dam and a maximum of around 16 years for the Wadi Hali

Table 7
The NPV, IRR, and ROI for the three proposed locations.

Location	IRR, %	NPV, $	ROI, %	SPP, year
King Fahd Dam	10.59	862,855.87	61	11.5
Wadi Hali Dam	8.03	446,058.41	31.5	15.4
Wadi Namar Dam	9.41	667,251.45	47.2	13

Dam and the Wadi Namar is approximately is about 13 years. The values of SPP, IRR, NPV, and ROI prioritize the favorable FPV plants at King Fahd Dam, Wad Namar Dam, and Wadi Hali Dam as the first, second, and third choices.

3.3. *Analysis of greenhouse gas emissions GHG*

The utilization of this form of green energy source for power generation results in the reduction of greenhouse gas emissions into the atmosphere. Based on the GHG emission factor of 0.799 t CO_2/MWh, the proposed FPV system of 1.0 MW installed capacity will displace 35,583.9 tons of CO_2 equivalent GHG emissions from entering into the local atmosphere during the lifetime of the plant at King Fahd Dam. Therefore, installing these systems at the proposed locations will save approximately 390,000 tCO_2 emissions from entering into the atmosphere during the lifetime of the FPV plants. Table 8 shows the amount of CO_2 emission saved as compared to how many barrels of oil and cars and light trucks were not used during 25 years of operation.

4. Conclusions

The investigation conducted in this study reveals the techno-economic feasibility of installing 1.0 MW capacity grid-connected Floating Photovoltaic (FPV) power plants across three possible Saudi Arabia sites. It estimated annual energy yield, Levelized Cost of Energy (LCOE), and greenhouse gas (GHG) emissions after carefully examining local climate circumstances, beginning economic factors, selected PV modules, and different technological constraints. The analysis determines King Fahd Dam as the most suitable location for FPV power plant development, with superior characteristics such as increased annual energy production and the lowest LCOE when compared to alternative sites. However, the remaining recommended locations show viability for FPV system implementation, albeit as secondary and tertiary options. The proposed FPV infrastructure is a commendable contribution to environmental sustainability because it efficiently offsets a significant volume of CO_2 equivalent GHG emissions while also reducing water evaporation from reservoir surfaces. Consequently, the results advocate for the initiation of a pilot plant installation at King Fahd Dam, serving as an invaluable experimental platform to navigate the technical and economic particulars associated with equipment selection, procurement, contracting, governmental approvals, and related logistical challenges. Such an endeavor promises to furnish engineers, utility providers, academics, researchers, and contracting entities with invaluable experiential insights, facilitating informed decision-making processes for future FPV plant deployments within the Kingdom and beyond. Future work should focus on further optimization of FPV system designs tailored to different climatic conditions to maximize efficiency and reliability. This includes considering variations in solar radiation, wind speeds, and temperature impacts, which are critical for performance in diverse environments. Additionally, long-term performance monitoring and data analysis are essential to assess the durability and reliability of FPV installations. Continuous data collection will help identify potential issues early and provide insights into maintenance needs and system longevity. Moreover, exploring hybrid FPV systems that integrate other renewable energy sources, such as wind, hydropower, or water management technologies could significantly enhance the overall efficiency and resource utilization of FPV systems. Furthermore, a proposed pilot plant at King Fahd Dam is expected to serve as a testing ground for future FPV projects, giving vital information on system performance, maintenance requirements, and operational issues in a dry environment. This pilot study will not only increase scientific understanding, but will also help with policy formulation, regulatory approvals, and commercial investments in FPV technology in Saudi Arabia and other similar regions around the world. Integrating these technologies can provide a more stable and diversified energy output while addressing water conservation issues. Collectively, these future research directions will not only enhance the technical and economic feasibility of FPV systems but also contribute to broader sustainability goals by optimizing resource use and minimizing environmental impacts.

Data availability statement

The data supporting the findings of this study are available upon request from the corresponding author. The authors are committed to ensuring the transparency and reproducibility of the study's results and will promptly respond to any reasonable requests for data sharing.

Ethics declarations

The authors of the study state that the research followed the ethical criteria and procedures established by the Heliyon Journal. We emphasize our commitment to upholding integrity, transparency, and rigor throughout the research process.

Table 8
CO_2 is saved by burning fuel.

Location	CO_2 emission saved, t CO_2	Oil barrels	Car and trunks not used
King Fahd Dam	35,583.9	82,736	6444
Wadi Hali Dam	29,286.0	68,093	5303
Wadi Namar Dam	32,524.5	75,623	5889

CRediT authorship contribution statement

Ahmed Saeed: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Shafiqur Rehman:** Writing – review & editing, Supervision, Project administration. **Fahad A. Al-Sulaiman:** Writing – review & editing, Validation, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Ahmed Saeed reports administrative support and article publishing charges were provided by King Fahd University of Petroleum & Minerals. Ahmed reports a relationship with King Fahd University of Petroleum & Minerals that includes: funding grants and non-financial support. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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